VOLUNTARY DEHYDRATION IN MAN[1]

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Running Head: Voluntary Dehydration in Man

ABSTRACT

The effects singly and in combination of heat, exercise, and hypohydration upon "voluntary dehydration" were studied in four acclimated, physically fit, young men. Ad libitum drinking during the heat experiments was 146 percent greater than it was in the cool experiments. **Hypohydration increased drinking 109 percent over the corresponding** hydration experiment, exercise increased water intake 41 percent over resting. Hypohydration and exercise were less effective than heat in stimulating drinking. During the 4-hour experimental periods, the subjects did not or could not drink enough to compensate for the water lost. Regardless of the magnitude of the water deficit at the beginning of the recovery periods, the rates of rehydration were the same. The more stressful the experiment, the greater the water consumption and, in general, the longer it took to regain the lost water.

INDEX TERMS

water balance heat exercise dehydration drinking
hypohydration voluntary dehydration

Voluntary dehydration may be defined as the delay in complete rehydration following water loss. Most of the larger mammals, including the dog (1), burro (2), and camel (20) can and do rehydrate rapidly following water loss. Man, on the other hand, rehydrates much more slowly when water is lost either by sweating (16) or by simple water deprivation (7). For example, when a man and a dog walked 32 km in a hot environment the dog maintained its weight balance but the man lost about 3 kg of his body weight even though water was available ad libitum to both (10). It was suggested (10) that since the dog lost water only through evaporation from the respiratory system, he drank enough water to maintain the concentration of sodium chloride in the extracellular fluid (E.C.F.). The man, in contrast, lost both salt and water by sweating and drank only enough water to maintain a constant osmolarity of extracellular fluid. As the salt content decreases, less water would be needed to maintain the E.C.F. osmolarity. On the other hand, Black et al. (7) studied simple water deprivation in one subject for 3 days and in another for 4 days. When water was again allowed, his subjects lost their desire to drink after consuming about a pint of fluid. It seems then that for the non-sweating, water-depleted individual, water intake must be controlled by mechanisms other than the maintenance of the osmolarity of the E.C.F. alone. Baker et al. (3) presented evidence that voluntary water intake by humans was increased with sodium chloride intakes of 393 and 530 milliosmols per liter. With salt intakes of 803 and 1,104 milliosmols per liter, drinking was considerably diminished. Sodium chloride was a very important adjunct to water intake and serum sodium was found to be highly correlated with total body water while chloride was not (8). Low salt intakes may also lead to water abstention (21).

The importance of maintaining an adequate water and salt intake while working in hot environments is well known (11, 15). Exercising men allowed water <u>ad libitum</u> became exhausted much earlier than exercising men drinking water equal to their sweat loss (6). Victims of heat prostration, heat exhaustion, and acute anhidrotic heat exhaustion are sometimes dehydrated and often exhibit little or no desire to drink (4, 21). Leithead (14) hypothesized that water depletion reduced sweating and predisposed one to heatstroke and death. If the factors controlling water intake could be fully elucidated, ways of maintaining adequate water consumption in man might be found. The purpose of this study was to try to define the phenomenon of voluntary dehydration in man with particular reference to the effects of heat, exercise, and water depletion.

METHODS AND EXPERIMENTAL PROCEDURE

<u>Subjects</u>. Four healthy young men served as subjects (Table 1). All were doctoral candidates in physical education and well acquainted with the testing procedures. The subjects were selected because of their high level of physical fitness. They were told that the experiments concerned only a general study of water balance. When questioned at the end of the study, each admitted ignorance of the importance of the <u>ad libitum</u> water intake measurements.

<u>Measurements</u>. The following measurements were made: urinary, sweat, and serum chloride (Aminco-Cotlove titrator); urinary, sweat, and serum sodium and potassium (Baird flame-photometer); urine and sweat pH (Beckman

Model 76); urinary, sweat, and serum osmolarity (Fiske osmometer); hematocrit (Wintrobe tubes). Expired gas was analyzed on a Fisher Model 25M partitioner which was calibrated using a modified Scholander gas analyzer (9). Hand and forearm sweat was collected in elbow length polyethylene bags. Insensible water loss was measured while the subjects slept the night before day 5. Nude body weight was measured on a steel-yard sensitive to one gram. Corrections were made for respiratory gas exchange by averaging oxygen and carbon dioxide values obtained just before retiring and again upon awakening in the morning. The oxygen consumption, carbon dioxide production, and insensible weight changes were not specifically included in the calculations. During the period in the chamber the sweat loss was determined by changes in body weight on a balance sensitive to 10 g; insensible weight loss was neglected over this period. There were no bowel movements while the subjects were in the chamber. During the recovery period oxygen, carbon dioxide, and insensible water were not measured. All the curves on the graphs were fitted by the method of least squares. Since the variables were continuous, product-moment correlation coefficients were employed.

Procedure. There were eight experiments: four in a hot (49 C) and four in a cool (24 C) environment with a relative humidity of 25 percent. The three independent variables, heat, exercise (6.4 km/hr on a level, motor driven treadmill), and hypohydration (4 percent of the body weight), and their controls, cool, sitting at rest, and hydration (water *ad libitum*), were combined three-at-a-time in eight possible combinations (Table 2). These conditions will be identified by the following abbreviations:

1) heat (H), cool (C); 2) exercise (E), rest (R); 3) hydrated (H), hypohydrated (D). Each of the eight experiments was conducted in an environmental chamber for a period of 4 hours (experimental period) followed by an 8-hour recovery period at 24 C. Only sedentary activity was allowed during the recovery periods. Water was consumed ad libitum throughout the experimental and recovery periods. The temperature of this fluid was maintained at 24 ± 5 C during the heat experiments and at 24 ± 1 C during the cool experiments and all eight recovery periods. Each subject was on a controlled diet 4 days prior to the day in the chamber. In the four hypohydration experiments the subjects were allowed 900 ml of water per day during the 4 diet days; in the four hydration experiments water was allowed ad libitum.

Diet. The controlled diet (Table 3) was composed of Sustagen (Mead-Johnson), saltine crackers (Premium), oleomargarine (Blue Bonnet), and either bouillon cubes (Wylers) or enteric coated sodium chloride pills (Libby). Subjects MP and JS consumed the 2900 kcal diet; WH, the 2500 kcal diet; and HW the 2900 kcal diet plus 360 g of Nutrament which brought his daily caloric intake up to 3200 kcal.

Acclimation. The acclimation process consisted of four 2-hour and one 4-hour walk at 6.4 km/hr at 49 C before the hot experiments and at 24 C prior to the cool experiments (Table 2). There was a day of rest between each exposure. The five heat exposures were conducted in October to take advantage of any natural acclimatization accruing from the preceding summer months. The five cool exposures took place in February so there would be few, if any, residual effects of the heat acclimation and acclimatization.[3] Measurements of blood pressure, body weight, skin and rectal temperatures, sweat chloride, and sweat rates failed to show the usual changes indicative of acclimation described by other workers (5, 16). This lack of change was attributed partially to residual acclimatization from the summer months, but mainly to the high degree of physical fitness of the subjects. The physiological changes induced by heat are similar to those induced by exercise (i.e., lower heart rate, lower blood pressure, lower rectal temperature, increased rate of sweating, etc.). Once these changes have been brought about by exercise, heat exposure would have little or no additional effect. Thus, with a constant heat stress, the degree of change induced by heat would be inversely proportional to the level of physical fitness.

Physical fitness. A modified 5-minute step test was administered to each subject shortly after arising on the experimental day (day 5). The bench was 43 cm high and the rate of stepping was 120 beats/min. The physical fitness index was calculated as follows:

$$\text{PFI} = \frac{\text{duration of exercise in seconds} \times 100}{\begin{array}{l}2 \times \text{sum of recovery pulse counts from} \\ 1 \text{ to } 1.5,\ 2 \text{ to } 2.5, \text{ and } 4 \text{ to } 4.5 \text{ min}\end{array}}$$

No warm-up was allowed before the test. The average PFI's for the four hydration experiments were 115, 115, 112, and 114 and for the four hypohydration experiments, 100, 102, 103, and 107. The decrease during hypohydration was not significant at the 5-percent level of confidence. The average PFI's indicated that the heart rate recovery was essentially stable over a 5-month period. The sitting heart rates were also fairly low: HW = 52, MP = 50, WH = 46, and JS = 48.

Three concepts regarding water metabolism are dealt with here; namely, body water, osmotic content, and water balance. Body water refers to the total amount contained in the body at any particular time. Osmotic content refers to the total crystalloidal osmotic activity in the normal human (18). Water balance equals total intake minus total output. In this study we are talking about the change in body water as reflected in the measurement of water balance. Water balance was calculated from intake minus sweat loss during the experimental period in the chamber and intake minus urine loss during the recovery period. The term hypohydration (R. E. Johnson - personal communication) refers to the state of diminished water content in relation to osmotic content. This condition was achieved in our subjects by restricting water intake while maintaining an adequate food and salt intake. Dehydration refers to the loss of water and a corresponding simultaneous loss of osmotic substance so the ratio of water to osmols in the body remains nearly constant.

RESULTS

Water balance. The points along the Y-axis, time P, (Fig. 1) represent the changes in body weight from day 1. The points on the 0-hour line represent the water consumed during breakfast of day 5 plus an additional 200 ml given to help secure a 1-hour control urine specimen prior to entering the environmental chamber. Curve CRH represents the "control" experiment. Water balance during CRH was maintained fairly well, probably within the limits of normal variability. In the other three hydration experiments, the subjects progressively hypohydrated during the experimental period. It should be recalled that water was consumed ad libitum throughout the entire experiment with the exception of the 200 ml during the preperiod, plus the water in the diet. In the hypohydration experiments progressive hypohydration was evident only in HED; the subjects rehydrated slowly in HRD, CRD, and CED. By the end of the experimental period there was a gain of about 0.5 liter of water. The HED curve during the experimental period followed the same slope as the HEH curve. Except for CRH and HED, the water balance of the six other experiments tended to congregate between 1.0 and 2.8 liters at the end of the experimental period. One might speculate that the body, under stress, "prefers" a diminished water content. The most striking phenomenon (Fig. 1) was that the slopes of all the recovery curves were not significantly different. One might expect the rate of repayment of the water debt to be faster with greater deficits, at least during the first few hours. Two meals of the standard diet were eaten during the recovery period, but they did not seem to alter the recovery water balance appreciably.

In general, the inhibition of the voluntary water intake was greater with greater stress. Four to six hours elapsed before the water deficit was reduced by 50 percent. The HED water balance was minus 3.8 liters at the end of the recovery period. R. Lemaire (personal communication) observed similar results and found it took up to 3 days for complete recovery of the lost water under conditions comparable to the HED experiment.

<u>Sweat</u>. Water intake was highly related (r = 0.91) to sweat loss only when the subjects were in a previously hydrated condition (Fig. 2, left). The small numbers - 1,2,3,4, - refer to hourly measurements. In the four hypohydration experiments the similar correlation between gross sweat loss and mean water intake was 0.22 (Fig. 2, right). Thus, hypohydration obscured the relation between gross sweat loss and mean water intake by causing an irregular water intake. There was no difference between the average sweat rates in comparable hydration and hypohydration experiments (Table 4).

<u>Urine</u>. There was a low negative relationship between the mean urinary excretion rates and the mean water intakes during the recovery periods (Fig. 3). These results are supported by a principal component analysis (13) of data from a previous field nutritional investigation (19) which indicated that there was no relation between the rate of urine excretion after exercise and water intake.

<u>Voluntary dehydration</u>. Voluntary dehydration was calculated as sweat loss (body weight loss) minus water intake (Fig. 4). Urine formed during the experimental period, usually less than 50 cc, was omitted from the calculation. The dashed line would have been followed if no water had been drunk. The heavier line is the regression of the HRH and HEH experiments. Its intercept on the X-axis is about 260 g/hr, indicating that at rates of sweating below 260 g/hr the lost fluid was replaced during <u>ad libitum</u> drinking. This observation confirmed similar ones made by Rothstein et al. (17). The product-moment correlation between voluntary dehydration and gross sweat loss was 0.92. The lighter

regression line represented all four hydration experiments combined. The correlation (0.91) was essentially the same as for the two heat experiments alone but the X-intercept was about 70 g/hr.

Exercise in the heat (HEH) and at room temperature (CEH) resulted in about 50-percent voluntary dehydration, but in the HRH experiment only 30 percent. There was no voluntary dehydration during the CRH experiment. Thus, exercise tends to increase voluntary dehydration.

Factors affecting water consumption. The water intake during the experimental periods in the heat experiments was 146 percent greater than it was during the cool experiments (Table 5). Hypohydration increased drinking 109 percent over the corresponding hydration experiment; exercise increased water intake 41 percent over resting. Thus heat had the largest single effect on water consumption during the experimental periods. Hypohydration and exercise were less effective than heat in stimulating drinking. Or, viewing it another way, exercise and dehydration were more effective in inhibiting voluntary water consumption than heat.

During all four hydration experiments, the subjects were more hypohydrated at the end than at the beginning of the experimental period. This was also true for the HED experiment. During the other three hypohydration experiments, the subjects were less hypohydrated at the end than at the beginning of the experimental period.

After the first hour in the two most severe experiments (HED and HEH), the subjects did not or could not increase their voluntary water consumption much above 750 ml/hr even though they were undergoing increasing negative water balance (Fig. 5). The peaks of drinking during the fifth hour occurred at lunch time. The evening meal was not eaten at any definite time so there would be no specific increase in drinking.

Subjective observations. The subjects were never very thirsty. According to a thirst scale as follows: 1 - none, 2 - slight, 3 - moderate, and 4 - much, the average degree of thirst, based on combined results from a questionnaire administered hourly during the experimental period, was from 2.6 (HED) down to 1.0 (CRH). The subjects were more thirsty when hypohydrated than when hydrated; they were more thirsty in the heat and when exercising than in the cool and resting.

The feeling of fatigue increased progressively during each of the four heat experiments. The cardiovascular measurements did not explain this fatigue which was greatest during hypohydration. The subjects felt cooler when hypohydrated in both the hot and cool resting experiments, but exercise removed that feeling of coolness.

DISCUSSION AND CONCLUSIONS

The observation that hypohydration confounds the relationship between sweat loss and water intake might indicate that a new homeostatic level was attained in the hypohydrated state and that there might be some adaptation to chronic water depletion. Men drank back less of the water they had lost after the second period of dehydration than after the first (17). At the present time evidence concerning adaptation to water deficit is inconclusive. The greater the stress the greater the water consumption (12). This increase in drinking could not be accounted for by a corresponding increase in the nonurinary water loss. For example, the average HEH sweat loss for 4 hours was 4,802 ml and the loss during HRD was 2,169 ml; the mean water intakes were 5,109 and 5,247 ml, respectively.

In the last 2 hours of all experimental periods and during the recovery periods, there was essentially no difference between the two water consumptions. Hypohydration increased the water intake during the first 2 hours of the experimental period over that of the corresponding hydration experiment. This immediate increase in drinking when hypohydrated is probably the reason that the relation between sweat loss and water intake is confounded. The capacity of the stomach and the rate of water absorption are also contributing factors because an upper limit of drinking of 750 ml/hr was observed. Further, during one of the acclimation walks, one subject vomited as he stepped off the balance at the end of his walk. He lost about 1.5 liters of fluid, the amount consumed during the previous 1.5 hours.

The observation that water intake is related to the volume of sweat lost during the experimental period and to urinary osmolarity, not urinary volume, during the recovery period suggests that both osmotic concentration and liquid volume are important in understanding the mechanisms of voluntary dehydration.

In the most stressful experiment (HED) the water deficit remained at least minus 4 liters through the experimental and recovery periods. During the HED recovery period, after the subjects had showered and dressed, they stated that they felt fully recovered and were not particularly thirsty even though they had a water deficit of 4 to 5 liters.

The observations suggest that there is a range of body water plus or minus some arbitrary set point within which functional deterioration does not occur. The cardiovascular measures indicated little, if any, decrement. The metabolic rates measured during the second and fourth hours of the experimental periods (Table 6) were essentially the same in comparable hydration and hypohydration experiments. Thus, in any particular experiment "steady-state" conditions were approximated after the second hour, and the levels of hypohydration attained did not alter appreciably the average metabolic rates. The fact that these subjects were in superb physical condition must not be overlooked. It is likely that less fit subjects would have shown some functional deterioration during the more stressful experiments.

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TABLE 1. Physical characteristics of the subjects

Initials	Age	Height, cm	Weight, kg	Surface area, m^2
HW	28	178	84.2	2.04
MP	26	173	73.3	1.87
WH	24	176	71.1	1.86
JS	26	173	70.6	1.83

TABLE 2. Experimental timetable

Week	Condition ($^{\circ}C$)	Date
	Acclimation	October 16-30, 1962
1	49°-rest-hydrated	November 1,2,3,4, 1962
2	49°-rest-dehydrated	November 8,9,10,11, 1962
3	49°-walk-hydrated	November 29,30; December 1,2, 1962
4	49°-walk-dehydrated	December 6,7,8,9, 1962
	Acclimation	February 5-19, 1963
5	24°-rest-hydrated	February 22,23,24,25, 1963
6	24°-rest-dehydrated	March 1,2,3,4, 1963
7	24°-walk-hydrated	March 21,22,23,24, 1963
8	24°-walk-dehydrated	March 28,29,30,31, 1963

TABLE 3. Diet composition

Kcal	Protein (g)	CHO (g)	Fat (g)	Na (g)	H_2O (g)	NaCl (g/day)
2900	107(15%)	368(56%)	95(29%)	4.71	448	14.1
2500	82(13%)	300(54%)	92(33%)	4.49	323	13.6

TABLE 4. Average sweat loss during the experimental periods (g/hr)

Hr/Exp.	HRH	HRD	HEH	HED	CRH	CRD	CEH	CED
1	449	410	1084	1076	62	33	348	348
2	615	614	1312	1284	34	37	392	429
3	575	576	1226	1151	57	57	400	406
4	564	570	1155	1195	47	41	342	347
$\bar{X}$	551	542	1194	1176	50	42	370	382

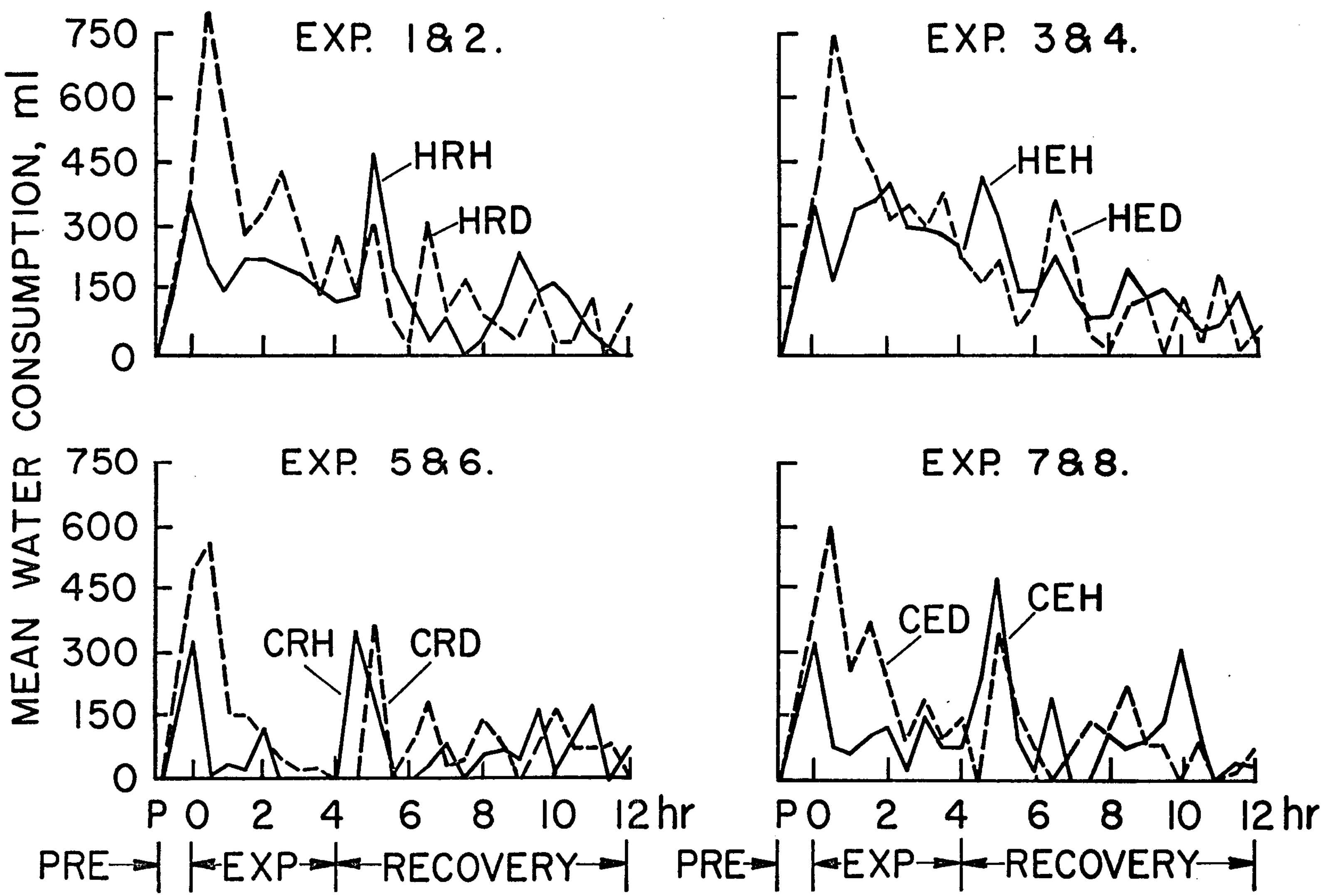

Fig. 5

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TABLE 5. Percent increase in water consumption due to heat, exercise, and hypohydration

Condition	(1 hr) Control ml/hr	(4 hr) Experimental ml/hr	(8 hr) Recovery ml/hr
HRH	366	344	246
HRD	343	770	228
HEH	356	584	302
HED	368	817	239
CRH	326	45	170
CRD	487	308	188
CEH	327	172	241
CED	397	497	192
Heat over cool		+146%	+28%
Exercise over rest		+41%	+17%
Hypohydration over *ad libitum*		+109%	-12%

The percentages were determined by adding the water intakes for the four heat experiments and for the four cool experiments and calculating the percent increases by the formula

$$\frac{\Sigma \text{ heat water intakes} - \Sigma \text{ cool water intakes}}{\Sigma \text{ cool water intakes}} \times 100, \text{ etc.}$$

TABLE 6. Average metabolic rates during the experimental periods ($kcal/m^2$ - hr)

Hr/Exp.	HRH	HRD	HEH	HED	CRH	CRD	CEH	CED
2	50.4	53.7	193.2	179.3	48.7	52.2	185.7	191.8
4	52.0	46.1	203.5	185.9	45.1	52.5	190.0	191.9
$\bar{X}$	51.2	49.9	198.4	182.6	46.9	52.4	187.8	191.8

FOOTNOTES

[1]This study constituted partial fulfillment of the requirements for the Ph.D. degree at the University of Illinois. The investigations were supported in part by Public Health Service Grants A-4210 and GPM-15,290.

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[3]Acclimation refers to artificially induced changes; acclimatization to changes resulting from the natural environment.

FIGURE TITLES

Fig. 1.- Gross cumulative water balance during the experimental and recovery periods.

Fig. 2.- Mean water intake versus gross sweat loss under hydration and hypohydration during experimental periods.

Fig. 3.- Mean water intake versus mean urinary excretion rate during recovery periods.

Fig. 4.- Gross sweat loss versus voluntary dehydration during hydration experimental periods.

Fig. 5.- Mean water consumption during the experimental and recovery periods for the eight experiments.

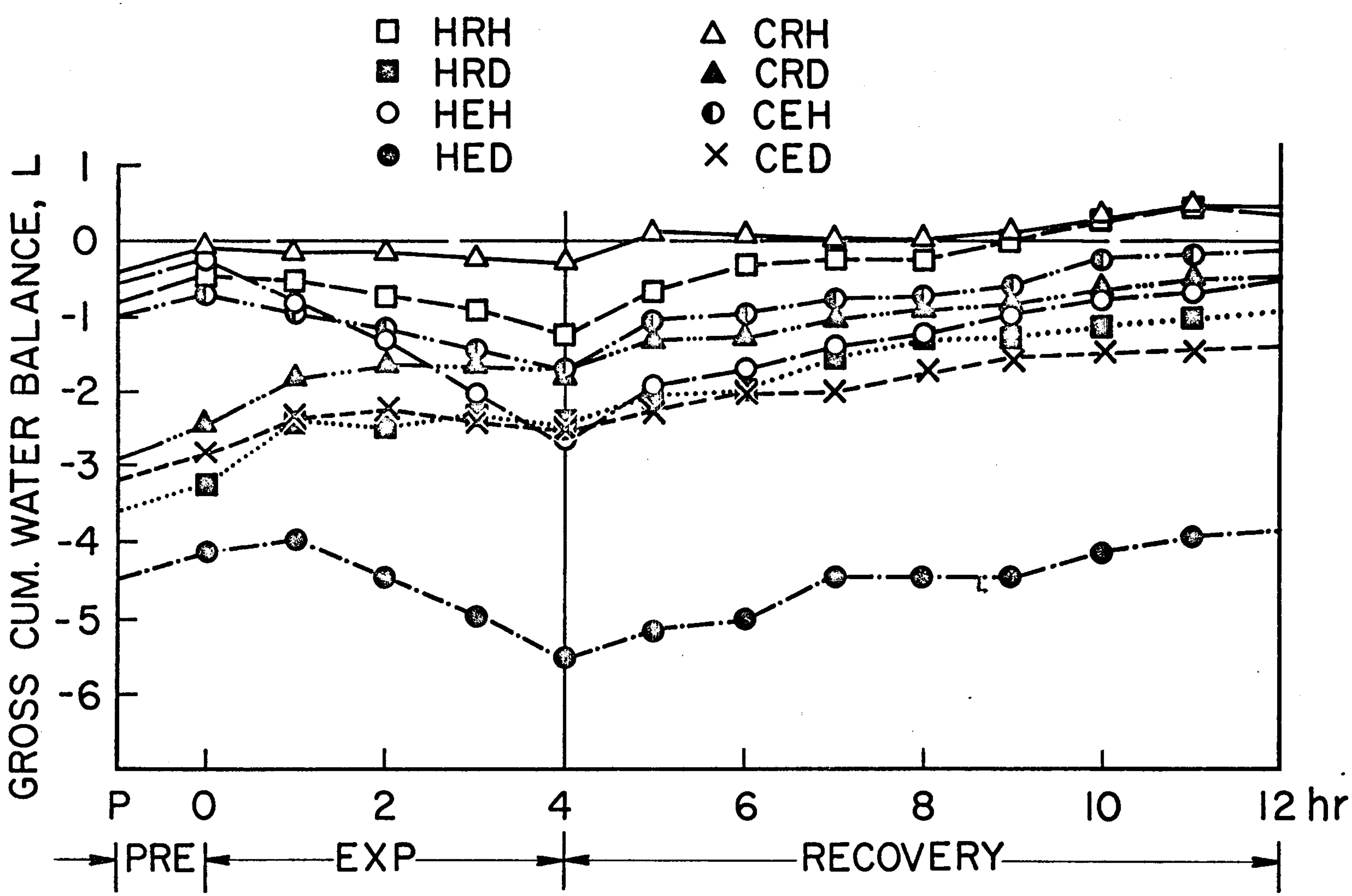

Fig. 1

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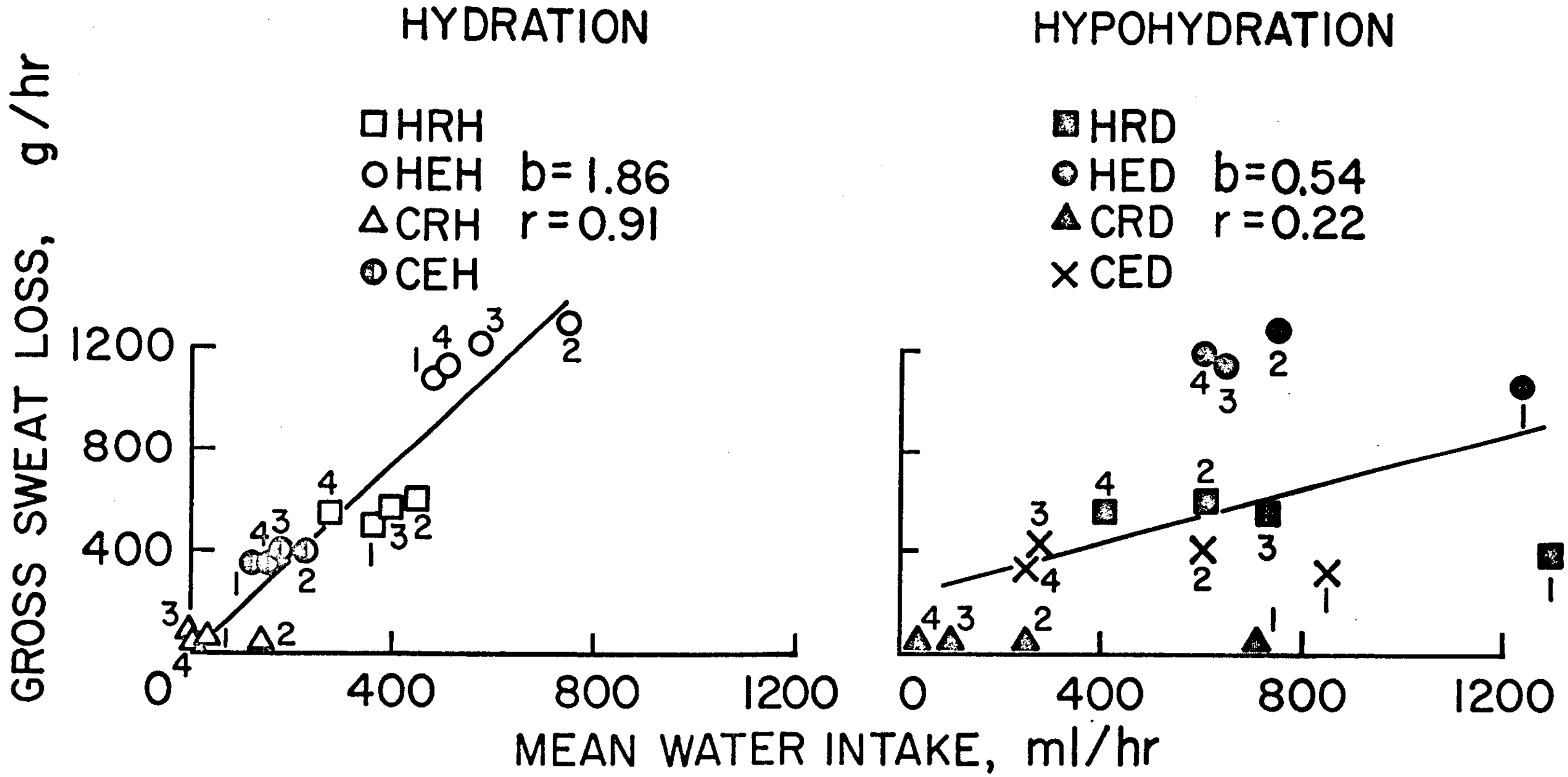

Fig. 2

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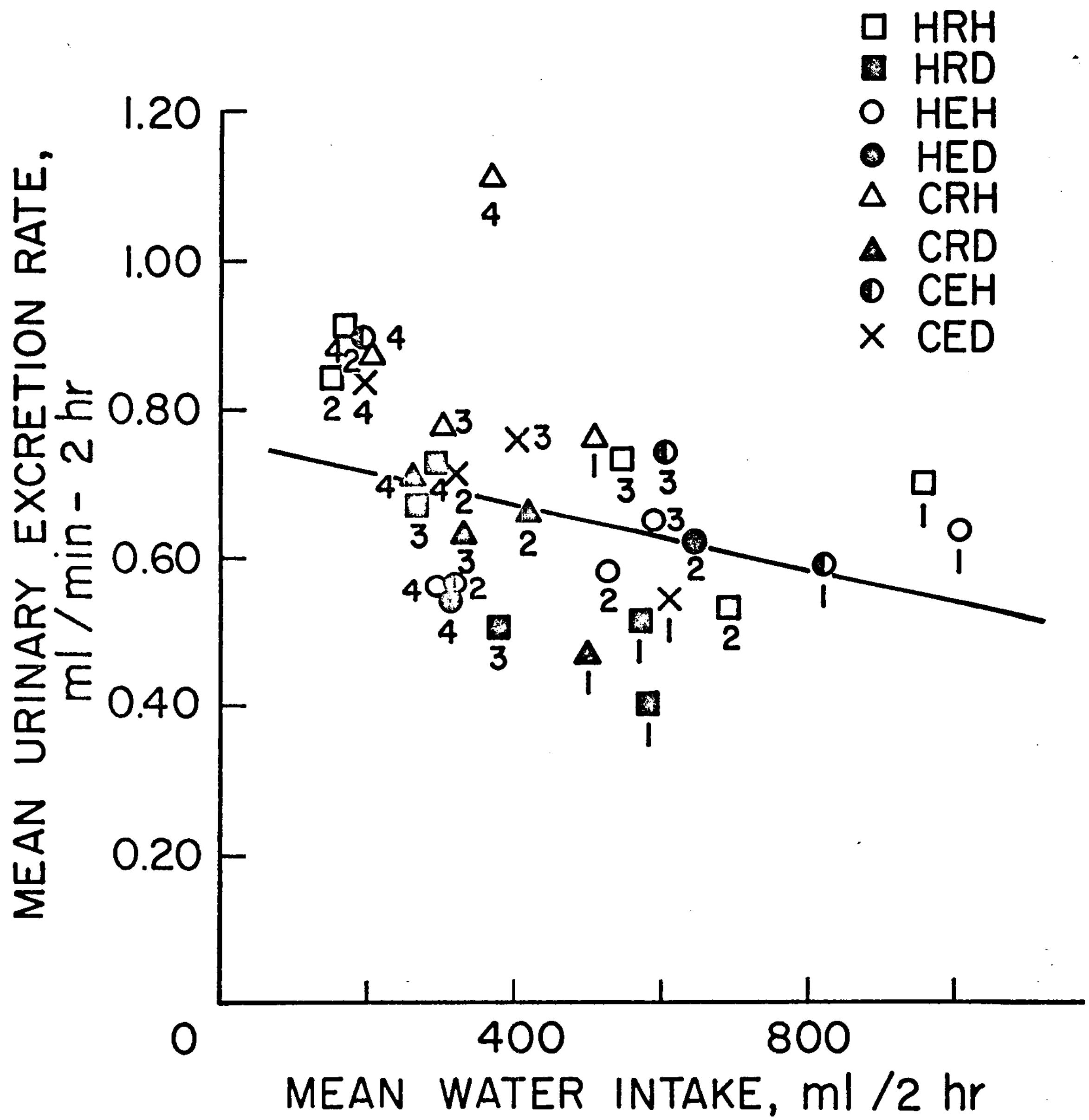

Fig. 3

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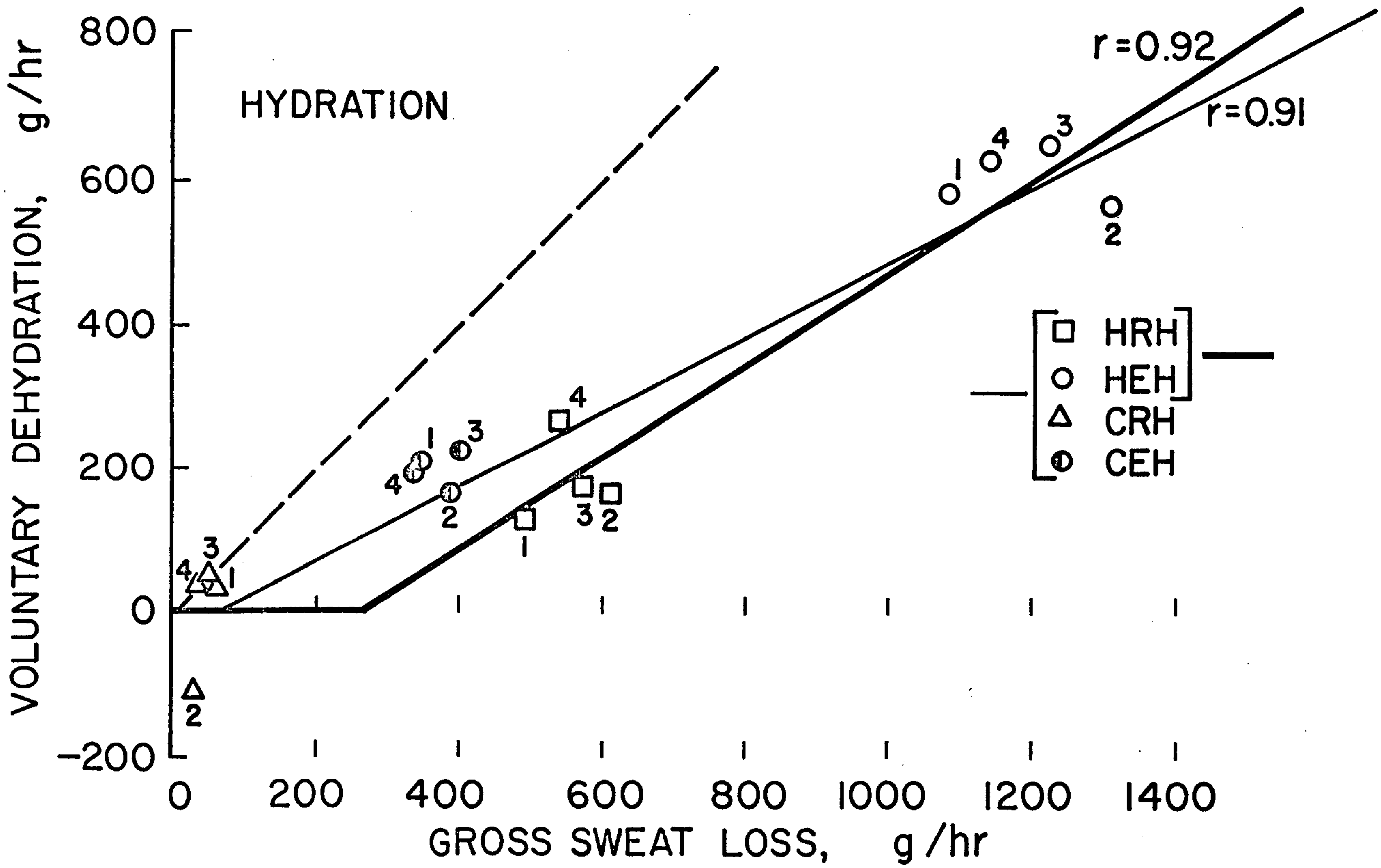

Fig. 4

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